



Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Review

A magnet system for HEP experiments

A. Gaddi

CERN, Geneva, Switzerland

ARTICLE INFO

Available online 21 March 2011

Keywords:

Magnet
Superconductivity
Detectors
Cryogenics

ABSTRACT

This chapter describes the sequence of steps that lead to the design of a magnet system for modern HEP detectors. We start looking to the main types of magnets used in HEP experiments, along with some basic formulae to set the main parameters, such as ampere-turns, impedance and stored energy. A section is dedicated to the description of the iron yoke, with emphasis on magnet-detector integration and assembly, steel characteristics, stray field issues and alternative design. In the second part of the chapter we start looking at a brief history of superconducting magnets and a comparison between warm and superconducting ones. Following that, we describe the commonly used superconducting cables, the conductor design and technology and the winding techniques. A section of the chapter is dedicated to the cryogenic design, vacuum insulation and other ancillary systems. We also describe the power circuit, with the power supply unit, the current leads, the current measurement devices and other instruments and safety systems. A section is dedicated to the measurement of the B field in HEP experiments and a final one briefly describes a few applications of these kind of magnets outside their application in high energy physics detectors.

© 2011 Elsevier B.V. All rights reserved.

Contents

1. Introduction	11
2. Magnet design	11
2.1. Solenoids	11
2.2. Toroids	12
2.3. Dipoles	12
2.4. Other geometries	13
3. Basic formulae	13
4. Magnetic yoke design	15
4.1. Magnet-detector integration	15
4.2. Steel characteristics	15
4.3. Assembly	15
4.4. Stray field issue	16
5. Superconducting magnets	16
6. Conductor design and windings techniques	17
6.1. Superconducting cables	17
6.2. Conductor design	17
6.3. Conductor technology	18
6.4. Winding techniques	19
6.5. Vacuum impregnation	19
7. Cryogenics, vacuum and other ancillary systems	20
7.1. Cryogenics design	20
7.2. Vacuum insulation	20
7.3. Thermal shields	20
8. Power circuit	21
9. Magnet protection issues and safety aspects	22
9.1. Instrumentation, controls and safety systems	22
9.2. Dump resistors	22

E-mail address: Andrea.Gaddi@cern.ch

9.3. Stray field	23
9.4. Helium release	23
10. Field mapping	23
11. Applications of HEP detector magnet technology outside particle physics	23
Acknowledgements	24
Further reading	24

1. Introduction

The position of magnets in detectors for particle physics experiments is of paramount importance. The magnet is often the most expensive component of the experiment, and it is important to ensure that it is appropriately optimized, both as a major product of engineering and as a complement to the other experimental equipment. This chapter aims to give an overview to the problems and possible solutions to design a magnet for HEP detectors rather than being a text for magnet experts. In most particle physics experiments one or more magnets are used to identify the particles coming out from the interaction. While uncharged particles traverse the magnetic field without being affected, particles having a positive charge will be deflected to one side and ones having a negative charge to the other. This provides the first information to identify the particle. The deflection of the charged particle depends on three parameters: the strength of the field, the length of the trajectory in the field and the momentum of the particle. The size and strength of the field can be precisely known, so by measuring the deflection one can find the momentum. Ideally for the experiment the magnetic field should be present, preferably in a direction perpendicular to the trajectories of the particles, as we will see in the Section 2. Moreover, with the increasing energy of particle accelerators and the need for greater and greater precision in the measurements, the experiments require stronger and stronger fields in larger and larger volumes. Many of these detector magnets therefore rely on superconducting windings. This chapter will describe the features of this class of magnet, along with the infrastructures necessary for their operation.

2. Magnet design

Since the beginning of the 19th century, scientists have made use of electric and magnetic fields to bend particle trajectories. A simple mass spectrometer is based on an electrical field that accelerates particles (in this case ions) and a dipole magnet that bends their trajectory, according to their mass. The acceleration and the deflection are due to the Lorentz force:

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v}\mathbf{B})$$

that acts in the direction of the electric field \mathbf{E} and orthogonally to the plane containing \mathbf{v} and \mathbf{B} . Particles with higher momentum will deflect less than low speed ones, particles with opposite charge will be deflected in opposite directions and neutral particles will go straight. Thus, by applying a magnetic field, particles can be identified on the basis of their charge and momentum.

It is interesting to note that, due to the limited value of the maximum applicable electric field (about 50 MV/m in vacuum), the deviation from the straight path, due to the electric field, is negligible for relativistic particles, compared to the magnetic one. This explains the extensive use of magnetic fields in modern particle detectors.

From the Lorentz equation we can easily derive that the bending radius r for a charged particle traversing a magnetic field B is simply given by:

$$qvB = mv^2/r, \quad \text{so that } r = p_T/qB$$

where $p_T = mv$ is the momentum component transverse to the magnetic field B . In order to measure the track of the particle, at least three points along its path are necessary. The error on the reconstructed path (momentum resolution) is thus proportional to:

$$(\delta p/p) \approx p_T/BR^2$$

where R is the radius of the volume, where the particle track is reconstructed. The latest equation shows that more than a stronger field, a larger tracking radius gives smaller errors. However the B field plays a role in the detector occupancy. The occupancy of a detector with a cylindrical shell shape, placed at a distance R from the beam axis, is defined as the number of occupied detector cells divided by the their total number and multiplied by their time response in two-bunch crossing time units and it results to be proportional to the charged particle dose, for thin detector shells. A stronger magnetic field will confine low p_T particles at smaller radii, while only high p_T particles will escape the tracking region and reach the calorimeter.

As explained above, the choice of the magnetic field for a detector is often a compromise between the best spatial resolution and the optimum occupancy. As a matter of fact, the value of the magnetic field has always risen up in the last twenty years, as a consequence of the increasing beam energy. The majority of HEP detectors have been designed with a solenoid coil that provides a uniform magnetic field along the beam axis, but there are examples of dipoles (specially for experiments on beam-to-target accelerators or when a precise measure of the particles axial momentum is required), large toroidal magnets or more complex design.

2.1. Solenoids

Solenoids are conceptually simple, elegant and very effective magnets. The vast majority of recent 4π detectors at HEP colliders have relied on solenoidal type magnets, producing a cylindrically symmetric field having the same axis as the colliding beams. In this design, only particles with a significant transverse momentum will be deflected, while those projected forward are almost untouched. The reason for the extensive use of solenoids is easy to understand: the symmetric 2-D field is fairly uniform and this facilitates reconstruction of the events; there is no material within the field volume to give rise to spurious secondary interactions, and the magnetic forces are relatively easy to contain. In addition, thanks to the large number of magnets that have been made and the experience with their operation, the associated technology is mature and steadily progressing. The momentum resolution is given by:

$$(\delta p/p)_{\text{solenoid}} \approx p \sin \theta / BR^2$$

where θ is the angle between the particle trajectory and the beam axis.

Within the limits of actual technology and road-transportable size, the cost of the solenoid of length L is roughly proportional to LR^2B^2 . It is therefore clear that, as concerns resolution, it can be preferable to invest in size than in central field, as said before. The basic technology for building superconducting solenoids is established, so it is relatively straightforward to design one for incorporation into a given detector. This will be addressed more in detail in another section. Solenoids are also adapted for

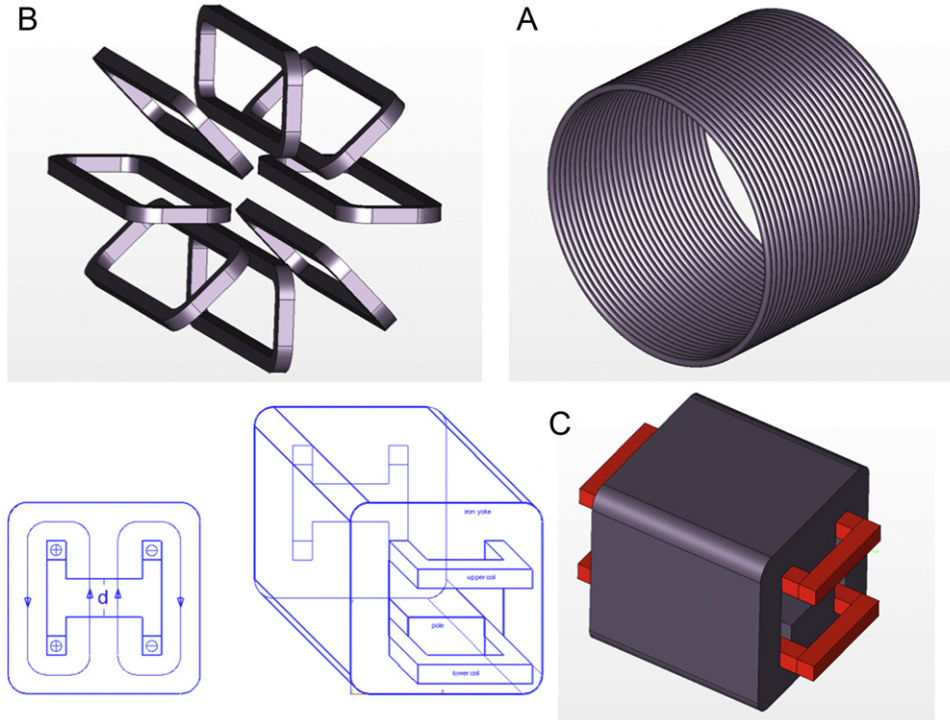


Fig. 1. Solenoid coil (A), toroid coil (B) and dipole coil (C).

making “thin” magnets through which particles pass with little likelihood of interacting, making for clean reconstruction of the events.

It is important to note that, when used on a collider, the effect of the solenoid on the circulating beams is small, but must not be neglected. The accelerator has to be provided with skew quadrupoles to correct for the coupling of vertical and horizontal betatron oscillations, and the orbit correction scheme must include capacity for compensating the effect of a small, but finite, crossing angle of the beams and the misalignment of the detector magnetic axis with respect to the machine one.

2.2. Toroids

In theory a toroidal magnetic field is ideal, both for a 4π detector at a colliding beam facility and for forward and fixed target detectors. The field is symmetric and perpendicular to the beam direction, but it is not homogeneous in the volume, as it goes like $1/r$. The integrated field along the trajectory of a particle increases as θ decreases, which is favorable because the likelihood of having high energy particles to analyze also increases as θ decreases. Charged particles produced on the axis are deflected in a plane. There is no need for an iron yoke to close the field and there is no field along the axis of the beams that could disturb the beam dynamics. The momentum resolution in this case can be written as:

$$(\delta p/p)_{\text{toroid}} \approx p \sin \theta / B_{\text{in}} R_{\text{in}} \ln(R_{\text{out}}/R_{\text{in}})$$

where B_{in} is the field at the toroid inner radius R_{in} and R_{out} is the outer radius. The ratio $R_{\text{out}}/R_{\text{in}}$ is usually between 3 and 5.

If toroids are not the most popular design among HEP detector magnets, this is not only because the toroid is a difficult magnet to build, but mainly because of the difficulty of making in practice anything resembling an ideal toroid, i.e. to make the inner conductor plane, and its supporting structure, sufficiently transparent, or to divide it up so as to cover a sufficiently small proportion of the azimuth, and to make it sufficiently long. This

material makes that some particles are absorbed or interact with the structure, an effect that can easily outweigh the benefits of conceptual elegance. Various studies made over the last years have concluded that the best practical approximation for a high field (and therefore superconducting) toroid, covering the central region of the detector of a collider experiment, consists of a small number of lumped, flat pancake coils (typically eight, see Fig. 1B). With care these can be made to cast shadows over as little as 30% of the azimuth, which can be considered acceptable. It implies, however, that a significant fraction of the central detector, in particular the electro-magnetic calorimeter, should lie within the inner radius of the toroid. At the end, the advantages of the toroid compared with the solenoid must be carefully evaluated. Iron yokes, present as a complement of solenoids, are also used as absorbers for calorimeters or muon spectrometers, the compensation of the effects of solenoids on the circulating beams is easy to understand and for a lumped racetrack toroidal coil the field is far from being uniform. Moreover, the field on the inside conductor of a typical lumped toroid is about four times the maximum field in the useful part of the magnet (compared with about 1.2 times for a typical solenoid), which is obviously highly unfavorable in the case of a superconducting coil. These kind of magnets have required extensive mechanical engineering studies concerning both the securing of the coils in their casings and the external structures which must safely support the magnets against a variety of forces : gravity and two categories of Lorentz forces internal to the coil and between different coils. The asymmetric forces due to offsets and to quenching one or more coils have also had to be fully understood.

2.3. Dipoles

The momentum resolution of a dipole with field B and length L is simply given by:

$$(\delta p/p)_{\text{dipole}} \approx p/BL$$

Fig. 1C shows a H-shape dipole magnet, commonly used in HEP experiments. It must be said that in this kind of magnets the field is not very uniform between the poles, if they are flat as in the sketch. However, by accurately shaping them, it is possible to extend the width of uniform field towards the aperture edges. While dipoles are not appropriate for the central part of 4π detectors, they are the magnets of choice for dedicated “forward” detectors that concentrate on the cone of particles emanating in the forward direction, as well as for fixed target detectors. The design of these magnets is quite challenging. Because of the large aperture and short length, the field is highly 3-dimensional, and in order to control the stray field the geometry of the yoke and coils needs to be carefully studied. In addition, a dedicated compensation scheme must be provided for the circulating beams. The preferred saddle shape for the coils is much easier to achieve with a resistive than with a superconducting coil. Unless a suitable geometry of the field can be achieved using either circular or eventually racetrack coils, it is unlikely that any experiment in today’s era could afford a superconducting version. In order to maximize the integrated bending field and minimize the stray field, if the magnet has iron poles these are often made sloping, to match closely the required acceptance and maximize the product BL .

2.4. Other geometries

Alternatives to the dipole for the forward region are the quadrupole and the toroid. The toroid provides better acceptance than the dipole, but suffers from its contribution to background through multiple scattering, and is obviously no use for very small angles. An advantage is that it does not require compensation. The quadrupole is open and is easier to compensate than the dipole, but the field reduces with reducing θ , and it needs to be complemented farther downstream with a dipole. In particular cases other geometries may be considered. These are almost always based on combinations of flat circular or racetrack coils, usually without an iron yoke. The field is strongly inhomogeneous, but can be accurately calculated analytically, and while onerous, tracking through it is feasible using modern computers. The design of the supporting structure for these coils can be quite challenging, and the space required must be taken into account in the design of the experiment.

Having given an overview on different HEP magnet geometry, in the following section we look to detectors equipped with solenoidal coils. The choice of the magnetic field has a great impact on the overall design of the detector. In the case of a solenoid, the value of the field at the beam axis and the solenoid free bore and length are among the first detector parameters to be set, when designing a HEP detector. Table 1 gives some examples of the three main parameters (B field, aperture, and length) of some representative detectors built from 1985 to now.

Once the choice on the B field geometry and strength has been done, it is necessary to evaluate the magneto-motive force that would generate the required field. This is simply given by the product of the value of the electrical current times the number of turns. For simple magnet geometries, a first evaluation can be

easily done with the use of some analytical formulae, as we will see in the next Section 3. However, for complex geometries, or when the required field has important gradients, the use of finite element codes is mandatory. Once given the value of the electrical current, the subsequent step is to design a conductor that would carry it and withstand the associated mechanical and thermal stresses. The main parameter is thus the current density that varies in function of the material and determines whether the cable can be resistive or has to be superconductive. In the conductor design there are also many other issues, such as the material radiation length, if the magnet is in between two particle detectors. Section 6 is dedicated to the conductor design, with particular attention to superconducting cables. The above design sequence is summarized in the schematics given in Fig. 2.

The process is necessarily iterative. If the current density is too high for the chosen conductor, the number of turns has to be increased, the geometry of the winding pack changed and the field has to be computed again. Once the current density, the coil inductance, the stored energy and the field quality are within the specifications, we can start to compute the electro-magnetic forces on the winding pack. At the same stage, it is necessary to verify the value of the peak field in the conductor and its influence on the temperature and enthalpy margin, the quench protection and discharge parameters, such as the maximum voltage and the percent of energy that has to be extracted and dumped outside the winding pack. For non-superconducting coils the process is the same, but the peak field, the temperature margin and the quench protection issues are replaced by more conventional cooling issues.

3. Basic formulae

The most recurrent formula used to compute the magnetic induction \mathbf{B} in a point at a distance \mathbf{r} from a conductor $d\mathbf{l}$, where flows a current i , is due to Laplace:

$$d\mathbf{B} = \frac{\mu_0 i d\mathbf{l}}{4\pi r^3}$$

In the specific case of a simple circular turn of radius r , the field B_0 at its center results to be:

$$B_0 = \frac{\mu_0 i}{2r}$$

whilst in the case of a solenoid of infinite length, i.e. a sequence of n circular turns per unit length:

$$B_0 = \mu_0 n i$$

This equation is interesting because it shows that the central field of an infinite length solenoid is independent from the solenoid radius. A first evaluation of the intensity of the magnetic induction B_0 at the center axis of a finite solenoid coil of inner radius r , outer radius R , finite length $2l$ and number of turns per unit length n , where flows a current i , is given by the following equation:

$$B_0 = \left(\frac{\mu_0 n i l}{R-r} \right) \ln \left(\frac{\alpha + \sqrt{\alpha^2 + \beta^2}}{1 + \sqrt{1 + \beta^2}} \right)$$

where $\alpha = R/r$ and $\beta = l/r$.

The limit for $\beta = \infty$, example of the solenoid of infinite length, gives again the value $B_0 = \mu_0 n i$. In a practical way, the actual field at the center of a solenoid coil of finite length, will always be less than the asymptotic value of an infinite coil, depending on the value of the parameter β . For $\beta > 2$, the actual field is only a few percent less than the asymptotic value, as we can see Fig. 3.

By adding an external iron yoke, the inner field is considerably enhanced, so that the limit value can be approached even if the ratio $2l/r$ is close to 1. This explains the presence of massive iron yoke

Table 1
Main parameters of some HEP detector magnets (solenoids).

	CDF	CLEO-II	ALEPH	ZEUS	H1	KLOE	BaBar	Atlas	CMS
B (T)	1.5	1.5	1.5	1.8	1.2	0.6	1.5	2.0	4.0
R (m)	1.5	1.55	2.7	1.5	2.8	2.6	1.5	1.25	3.0
L (m)	4.8	3.5	6.3	2.45	5.2	3.9	3.5	3.66	12.5

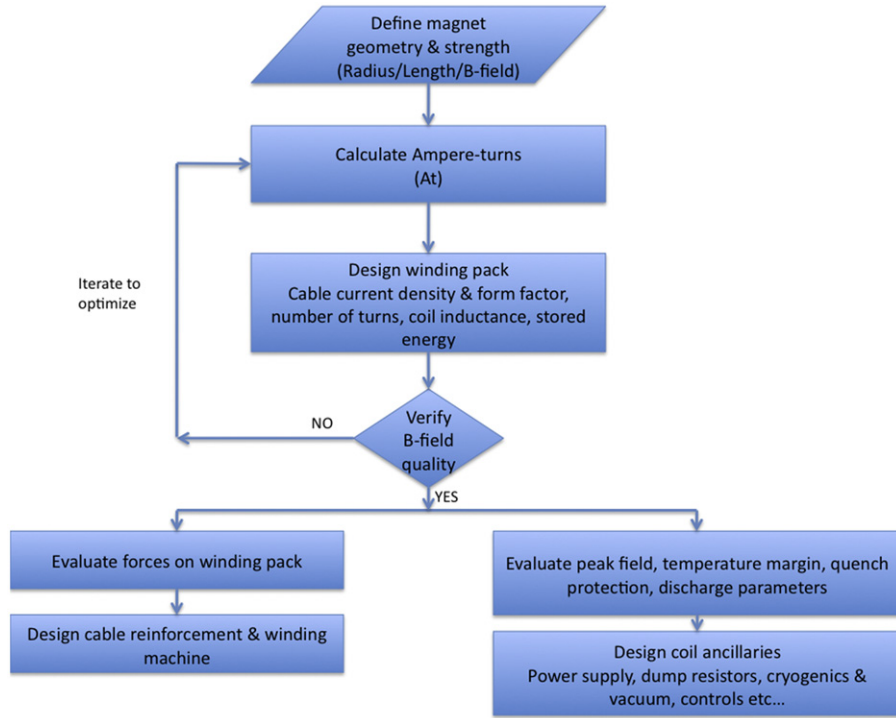


Fig. 2. Schematics process for a superconducting coil design.

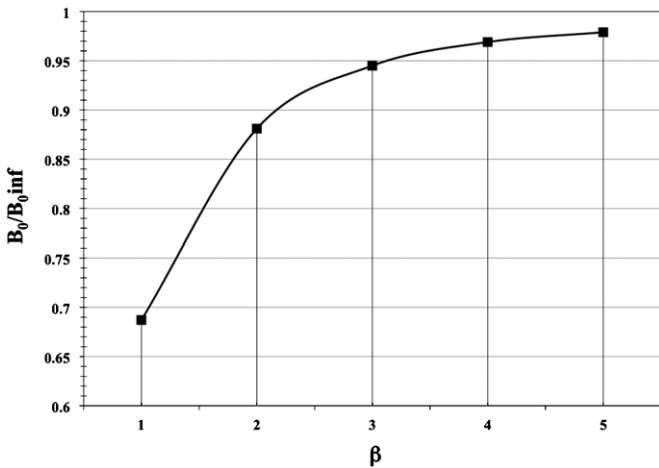


Fig. 3. Plot of B_0/B_{0inf} as a function of β .

around of most of the magnetic apparatus, not only in HEP experiments. The yoke allows also shaping the field, i.e. to create gradients or to enhance the uniformity in specific areas, such as the tracking volume of a particle detector, where usually high field homogeneity is required. The field homogeneity for a solenoid can be expressed in several ways, one of the most intuitive being the ratio between the difference of the axial component of the field in the tracking volume (B_z) and the value on the beam axis (B_0), integrated over any possible radial trajectory:

$$\text{Field homogeneity} = 1 - \frac{1}{R} \int_0^R \frac{B_z - B_0}{B_0} dr$$

The effect of a magnetic yoke is even more important in a dipole magnet. In this case, the magnetic induction is simply proportional to the magneto-motive force Ni of each coil and inverse with the gap aperture d , i.e. the distance between the two

magnetic poles of the iron yoke, see Fig. 1C:

$$B \approx 2\mu_0 Ni/d$$

The above formula neglects the magnetic path into the iron yoke, whose reluctance is supposed to be much smaller than the air gap. This is not the case when the iron yoke is saturated, that is typically the case for accelerator dipoles, where the current distribution around the poles shapes the field.

Two other important parameters can be calculated with analytical formulae: coil inductance and stored energy. The coil inductance plays a role in defining the transient states, i.e. each time there is a variation of current within the winding pack. The magnetic total stored energy and the magnetic stored energy per unit of mass are also important because they are related to protection issues.

The coil inductance depends only on the geometrical parameters of the winding. For a thin solenoid it can be easily calculated as:

$$L = \mu n^2 \pi 2l R^2$$

The density of an electro-magnetic field in air is given by:

$$w = \frac{1}{2} \left(\frac{B^2}{\mu} + \epsilon E^2 \right)$$

where B^2/μ is the magnetic component and ϵE^2 is the electric one.¹ By integrating over the full volume, we obtain the total energy stored in the magnet:

$$W = \frac{1}{2} \int_V \frac{B^2}{\mu} dv$$

¹ It is interesting to compare again the two contributions, that is some Joule/cm³ for the magnetic energy density (at 2 T) and not more than a few 10⁻² Joule/cm³ for the electric one (at about 500 kV/cm). This confirms the superiority of the magnetic with respect to the electric field in most of practical application such as motors, transformers, etc.

For a solenoid coil the result is:

$$W_{\text{solenoid}} = \frac{1}{2} \frac{B^2}{\mu} \pi 2lR^2$$

remembering that in this case, we can substitute B with μNi , this gives an interesting relationship between the stored energy and the coil inductance in a solenoid:

$$W_{\text{solenoid}} = \frac{1}{2} Li^2$$

Typical values for recent HEP detector magnets cover the range between 100 and 2.5 GJ. The magnetic stored energy per unit of mass is given by the above value divided by the winding mass (W/M). In superconducting magnets this corresponds to the average cold mass temperature after a quench, as we will see more in detail in the following sections. It is also an indication on how much attention has to be put into the quench protection system.

4. Magnetic yoke design

4.1. Magnet-detector integration

We have seen in the Section 3 that the presence of a magnetic yoke allows for a more homogeneous field in the detector tracking region. The yoke has also an important function of supporting the different detectors that compose the experimental set-up. Usually the magnetic requirements are more stringent than the mechanical ones, the thickness of the yoke being chosen to carry the maximum flux. The advantage of a thick magnetic yoke results in saving current in the coil and keeps the stray field outside the detector to low levels. The stray field affects all the equipment located in the experimental area and could make difficult or dangerous the access to some detector components when the magnet is on. However there are always limitations on the overall quantity of iron that can be put around a detector. First of all the maximum detector weight cannot exceed the limit given by civil engineering, both in terms of admissible weight on the beam area and of long term stability of the cavern geometry, that needs to be assessed by periodical survey measurements. Moreover the detector needs to be accessible inside, so the yoke has to be easily opened to grant accessibility to the innermost components. These two requirements, massive yoke to carry a maximum of magnetic flux and light weight for easy opening are conflicting and require a careful magnet-detector integration study. A good magnet yoke design means easy maintenance and optimum operation reliability, without compromising the detector physics performance.

Another important functionality of the yoke is to act as a radiation shield. A thickness of more than one meter of solid iron is necessary to lower the value of charged particle radiation outside the detector, whilst the neutron field remains important, specially in hadronic colliders. In addition to that, modern safety codes for HEP sites require a complete safety analysis regarding the occurrence of an earthquake. The magnet yoke is designed in order to limit to a minimum the risk of damages, in particular structural parts have to keep their integrity after a seismic stroke. For this purpose, finite element analysis of the yoke structure are done with the aim of evaluating its natural frequency and vibration modes along with its response to a typical seismic excitation.

In addition to supporting the different sub-systems of the detector, the magnetic yoke is often the support of the last accelerator components, close to the interaction point. This is particularly true for lepton colliders, where the focusing quadrupoles are located at a few meters from the beam collision point.

In this case a special care has to be put to isolate the final focusing magnets from any noise or vibration that could be transmitted or even amplified by the massive magnetic yoke, thus reducing dramatically the accelerator luminosity at the interaction point. For future electron-positron linear colliders, what above is one of the most challenging engineering issues.

4.2. Steel characteristics

Not all kinds of steel alloys are adapted as iron yoke material. Most magnets use steel alloys with a low content in carbon as flux return yoke, typically less than 0.1%. The magnetic performance of steel is highly variable and affected by both the chemical impurities in the iron and by its mechanical and thermal processing. The magnetic characteristics of steel are dominated by its carbon content and other chemical impurities. Because of this, generally a magnet steel is designated by its equivalent carbon content. The magnetic performance is also affected by mechanical processing. Rolled steel may have different directional magnetic properties. Isotropy can be restored by annealing the rolled steel at some temperature high enough to re-grow the crystalline grain structure. This has an impact on the maximum size of yoke pieces that can be heat-treated in an oven and on their fabrication cost.

Also the coercive field plays an important role. Coercivity, measured in A/m, indicates the resistance of a ferromagnetic material to become demagnetized, i.e. the intensity of the external magnetic field necessary to reduce the residual magnetization of the material to zero. Steel alloys for iron yokes must have a coercive field as low as possible. This quality of the steel is of primary importance for accelerator magnets, but it stays relevant for detector magnets as well (Fig. 4).

4.3. Assembly

The HEP experiments in the early 80's where build directly on the interaction point, or close by. A few years later, large assembly hall have been built to allow a safe and comfortable construction of heavy detector magnets that were then moved to the beam pipe once completed. As many accelerator complex are located underground, there is a cost limitation on the size of these assembly halls and the associated lifting devices. By these considerations, some large and heavy experiments have been conceived to be assembled on surface and then lowered into the cavern in slices. The CMS experiment at CERN is an example of this kind, it has been assembled and tested on surface and then lowered down 100 m into the experimental cavern (see Fig. 5).

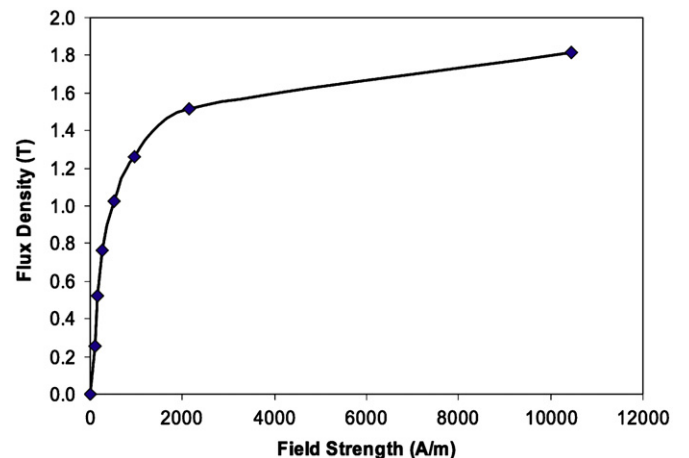


Fig. 4. Saturation curve B - H for typical magnet steel.

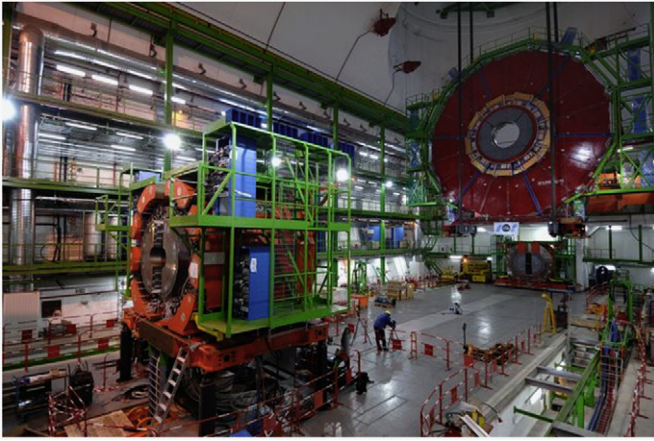


Fig. 5. CMS magnet: lowering magnet elements from surface down to the experiment cavern, one hundred meter below ground.

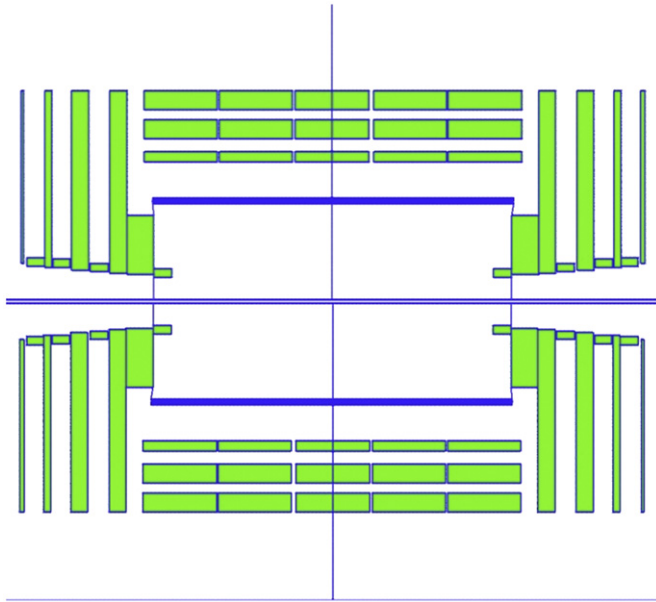


Fig. 6. Axial cut-out of the CMS detector magnet. The cylindrical blue part represents the superconducting coil, while the green boxes stand for the yoke massive iron pieces. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The design of the magnetic yoke, which is split into 13 slices, allows for an easy opening and accessing to the internal detectors. Fig. 6 shows an axial cut-out of the CMS magnet yoke. The blue thick line is the 4 T superconducting solenoid, while the green boxes are massive iron pieces. The slots between iron parts are fitted with muon chambers. The sketch visualizes very well the open structure of the yoke, with an overall length of 20 m and a diameter of 14 m. This choice was made in order to have an easy access to the inner detector and an overall yoke weight not exceeding 10,000 tons. As a consequence of this open design, a significant fraction of the return field, specially in the forward region, escapes the saturated iron yoke and generates a non-negligible stray field (see Fig. 7), that imposes some precaution, as we will see in Section 9.

4.4. Stray field issue

Recently some studies have been done to find alternative solutions to the presence of a massive iron yoke. CMS yoke

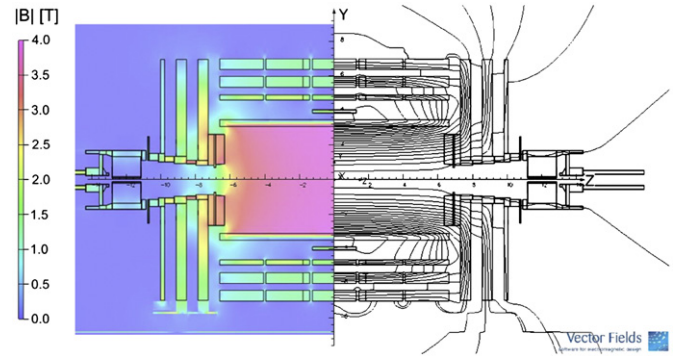


Fig. 7. CMS magnet: main and stray field calculations.

weights some 10,000 tons, for the next generation of leptons linear colliders, detectors with a yoke weighting up to 15,000 tons have been proposed. The cost of bare steel becomes in this case a significant fraction of the whole detector cost, along with the tooling necessary to assemble and move such a heavy detector. The function of closing the magnetic field lines outside the solenoid inner volume can also be achieved without a yoke, by adding a larger solenoid, coaxial with the main one. In this arrangement the effective field in the inner volume is the algebraic sum of the original inner field and the outer one, whilst the stray field outside the larger solenoid results to be very low. There are many engineering problems to overcome to realize such a design at the scale of the modern HEP detectors, but undoubtedly that is the case also for very large magnetic yokes.

5. Superconducting magnets

Although the idea of making electromagnets with superconducting wires was proposed by Heike Kamerlingh Onnes, shortly after he discovered superconductivity in 1911, a practical superconducting electromagnet had to await the discovery of type-II superconductors that could stand high magnetic fields. The first successful superconducting magnet was built in 1954, using niobium wire and achieved a field of 0.7 T at 4.2 K. The first application large to HEP detector was done at Argonne National Laboratory in 1968, where a split-coil superconducting solenoid was providing a 1.8 T field to a large liquid hydrogen bubble chamber. The superconducting cable was immersed into a liquid helium pool and it was able to carry a current of 7.75 A/mm². Gradually the current density rose to 12.5 A/mm², till the first cable stabilized with an aluminum insert was developed for the Cello experiment, in 1978. The new conductor design allowed for the indirect cooling of the winding pack, with large benefits for what concerns the compactness and the mechanical stability of the coils. All the following superconducting magnets followed this idea that proved to be very effective. The current density has reached now values of the order of 30 A/mm², the nominal field 4 T and the stored energy the outstanding value of 2.5 GJ.²

We compare the above numbers with what has been achieved with a resistive coil, taking as an example the large solenoid of the Alice magnets at LHC (former L3 experiment magnet at LEP), that is characterized by a current of 30 kA, current density 0.55 A/mm², nominal field 0.5 T, voltage drop 140 V, stored energy 150 MJ and power consumption 4.2 MW. It is clear that a superconducting coil outcores in the current density (that means thinner winding pack), voltage drop and power consumption (i.e. lower

² CMS detector magnet at LHC accelerator, year 2006.

operation costs). On the other end, a resistive coil is cheaper in terms of conductor manufacture and associated services. In other words, the superconducting coil is the best choice when the operation costs are dominant over the construction ones, or there are technical requirements (high field, thin coil) that make the resistive option not practicable.

The winding pack of a superconducting coil, indirectly cooled by a flow of liquid helium, is not conceptually very different from that of a resistive coil, if we make abstraction of the conductor material and the operating temperature. The current flows in an insulated conductor, wound inside a mandrel or self-supporting. Cooling pipes are attached to the winding pack to extract the heat generated by the resistive coil or to keep the superconducting coil at the required temperature. Whilst the conductor for a resistive coil is rather easy to design, that for a superconducting one is often a major technological challenge.

6. Conductor design and windings techniques

6.1. Superconducting cables

Among dozens of high field superconducting alloys and compounds developed and tested late 1960s, only two Nb alloys have been practically employed in HEP detector magnets. NbTi and Nb₃Sn have, respectively, a critical temperature of 9.3 and 18 K and a critical field of 12 and 22 T at 4.2 K and zero-current. By looking to this, one could argue that Nb₃Sn would be the best choice, but in reality all the superconducting HEP magnets have been wound with NbTi strands. The reason is that this material is much easier to work than Nb₃Sn, which shows high brittleness and requires a complex winding operation. Moreover typical detector magnets do not require fields larger than 5 T, so that the value of the critical current at 5 T and 4.2 K is still large enough to have a compact winding pack. The situation is different for accelerators magnets, where fields over 10 T can be required, thus the only available material is Nb₃Sn. In the recent years a new category of high temperature superconducting cables (HTSC) have been developed in many research centers. Although their characteristics look very promising, there are still technological issues to be overcome before they could really challenge the Ti-based superconductors in HEP detector magnets. However they can already now replace low-temperature superconductors for a number of specific applications, such as current-leads feeders and bus-bars.

Fig. 8 plots the critical values of temperature, current density and B -field for a typical Nb–Ti superconducting cable. These three variables are strictly linked together so that if we want, for instance, to increase the current (and consequently the field) we have to lower the temperature to avoid quenching the cable. As the field value is imposed by the detector design and the temperature given by the liquid helium boiling point at atmospheric pressure (4.2 K), the current density upper value is univocally determined. This corresponds to some kA/mm², that looks exceptional compared with what reached by the first superconducting magnets (cfr. Section 5), but the true value, i.e. the actual current density of the engineered conductor is much lower, as other materials have to be added to the bare NbTi alloy in order to assure its thermal and mechanical stability.

6.2. Conductor design

We refer here to the design of a superconducting cable suitable for a solenoid coil. We have seen in Section 3 that for this specific coil geometry, the central field B_0 is proportional to the number of ampere-turns linear density Nl . This proportionality is

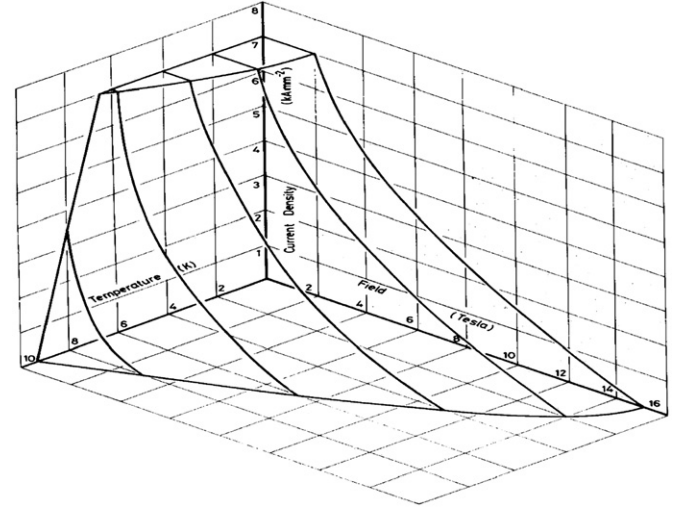


Fig. 8. Relationship between critical current, temperature and field in a NbTi superconducting cable.

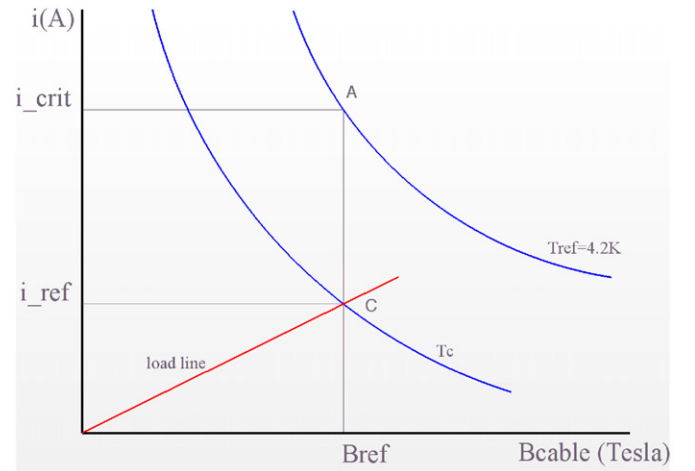


Fig. 9. Conductor load-line, critical current and temperature margin.

represented by a straight line (load line) in the i vs B_{cable} graph (Fig. 9). We also know, from numerical computations, that the maximum field in the conductor can locally reach 1.2 times the nominal one, in particular at the solenoid ends, where a strong radial component of the field appears. We indicate with B_{ref} the maximum field seen by the conductor at the nominal central field B_0 . The load line gives the current i_{ref} in the magnet that results in a peak field B_{ref} in the conductor. In the same graph we plot two isothermal lines that represent the relationship between i_{critical} and B_{ref} at constant temperature. The line intercepting the point A gives the critical current of that cable at the nominal temperature of 4.2 K and the peak field B_{ref} , the line passing by C indicates the critical temperature $T_c > T_{\text{ref}}$ at which the cable is still superconducting. The difference $\Delta T = T_c - T_{\text{ref}}$ gives the temperature margin of that cable at its working field. The larger this value is, the greater is the superconducting coil stability against perturbations. Typical values in HEP detector solenoids for the above mentioned variables are $i_{\text{critical}} = 3i_{\text{ref}}$ and $\Delta T = 1.5\text{--}2$ K.

An important parameter to be checked, for the assessment of the superconductor stability, is the enthalpy margin, i.e. the energy necessary to increase a unit volume of coil mass from its operating temperature to the transition, or current sharing, and temperature. Actually it is allowed to have some heat released

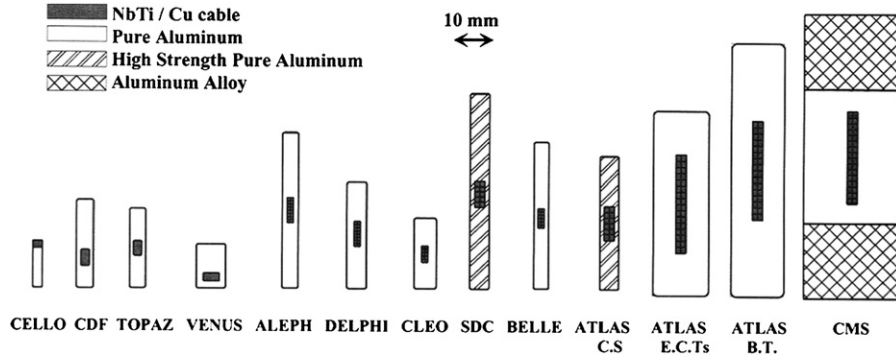


Fig. 10. Conductor cross-sections of some superconducting magnets for HEP detectors.

inside the winding, either localized or distributed, but under the requirement that the superconducting cable maximum temperature does not exceed the current sharing temperature (T_s):

$$T_s = T_c - (T_c - T_{\text{ref}}) \frac{i_{\text{ref}}}{i_{\text{crit}}}$$

The critical temperature T_c , as function of the magnetic field, can be empirically evaluated from the below formula, where T_{c0} is the critical temperature at zero-field (e.g. 9.3 K for NbTi):

$$T_c(B) = T_{c0} \left(1 - \frac{B}{B_c}\right)^{0.59}$$

The balance between the number of turns n and the electrical current i , depends on the conductor form-factor and its technology. A thin conductor winding would carry less current and need more turns, a thick conductor would do the opposite. We shall remember as well that the maximum number of turns is limited also by the coil inductance L , a parameter that plays a key role in the transient states, namely during a fast discharge (cfr Section 9.2).

The typical superconducting cable for HEP magnets comes under the name of “Rutherford cable” and is made by a thin braid of several twisted NbTi–Cu strands, about 1 mm in diameter. The number of strands ranges from 12 to 40,³ depending on the required current. The “Rutherford” is embedded into a high purity aluminum cladding, called stabilizer, that has the function of giving a solid shape to the cable and helping in sharing the current between the NbTi–Cu strands and the aluminum, in case of local transition from superconductive to resistive state of the strands, by limiting the joule effect and preventing a generalized quench. As a consequence of the “Rutherford cable” geometry, the form factor of such a conductor with its stabilizer is a rectangular cross-section, with the ratio between height and width that can be adjusted within certain limits (see Fig. 10). The quality of the high purity aluminum is measured by a fundamental parameter that gives the ratio between its resistivity at 4.2 K and at room temperature (RRR =Residual Resistivity Ratio). The best aluminum grades show a RRR above 2000, but acceptable values start at 400.

Following the electrical (critical current) and thermal (temperature margin) design, the conductor has to be designed also to withstand the magnetic forces acting on the winding pack. Directly from the Lorentz force equation seen in Section 2, we understand that the axial field component generates radial forces and the radial field component (essentially present at the solenoid ends) is responsible for axial forces. From a practical point of

view, the solenoid coil tends to expand due to the radial magnetic pressure and to shrink under the load of the axial forces at its ends. For a homogenous conductor, with a rectangular cross-section h – w , the stress s due to the radial magnetic pressure is given by:

$$2\pi r \frac{B_0^2}{2\mu_0} = 2\pi\sigma h, \quad \text{so that } \sigma = \frac{r B_0^2}{h 2\mu_0}$$

The elongation ε is simply:

$$\varepsilon = \frac{\sigma}{Y} = \frac{r B_0^2}{h 2\mu_0 Y}$$

where Y is the material Young modulus. There is an interesting relationship between the stored magnetic energy per unit mass (W/M) and the hoop stress for a “thin” solenoid, with mean radius r , thickness h , total length L and specific mass ρ . Recalling that:

$$W_{\text{solenoid}} = \frac{1}{2} \frac{B_0^2}{\mu_0} \pi L r^2 \quad \text{and} \quad M = 2\pi r h L \rho$$

we have

$$\frac{W}{M} = \frac{1}{4} \frac{B_0^2}{\mu_0} \frac{r}{h \rho}$$

and consequently $(W/M) = (\sigma/2\rho)$

This equation means that the stored magnetic energy per unit of mass is directly proportional to the conductor hoop stress. On the other way around, given the maximum allowable hoop stress in the conductor (and its specific mass), we can obtain the value of the maximum stored magnetic energy density. Actual values for large HEP detector solenoids are comprised between 4 and 10 kJ/kg, resulting in a hoop stress between 20 and 50 MPa, for aluminum stabilized superconducting cables.

The axial compression force adds a stress that is given by the total force divided by the conductor lateral surface. Typical values of compression stresses are between 10 and 30 MPa. In addition, shear stresses are present in the winding due to differential thermal contraction coefficients between materials. These stresses are particularly important at the insulation between turns and they can eventually lead to a crack in the material.

6.3. Conductor technology

We have said in Section 5 that one of the main technological break-through in the design of superconducting cables for HEP detector magnets has been the passage from direct to indirect cooling. This has been possible, thanks to the development of the co-extrusion of the “Rutherford” cable with the high purity aluminum. The extrusion process has to assure a perfect bonding of the two elements, without compromising the electrical performances of the superconducting cable.

³ The number of 40 strands is a limit due to the cabling machine technology. At present, cables with upto 40 strands and 3 km length have been produced.

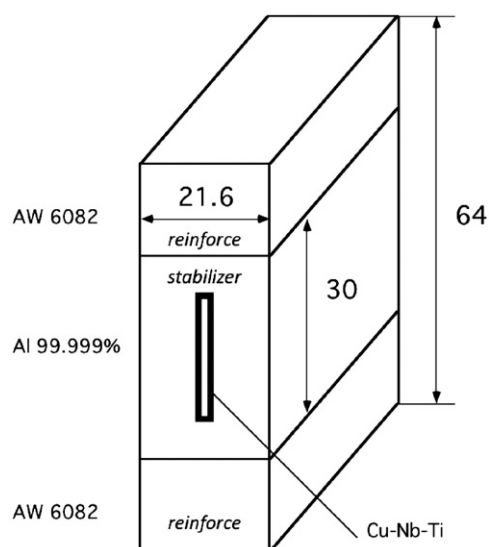


Fig. 11. CMS reinforced conductor (dimensions are in mm).

The mechanical characteristics of the pure aluminum stabilizer being limited, in order to sustain the magnetic forces during coil energization, the winding has to be enclosed into a surrounding cylinder that keep the hoop stress within the limits. By increasing the size and the nominal field of the coils, the magnetic forces become too large to be withstood by the pure aluminum conductor, even with the help of the support cylinder. In order to solve this problem, two different conductor designs have been investigated for LHC detector magnets at the end of the 90s. For extra-thin coils, that have to guarantee the maximum transparency to traversing particles, the choice was made to use doped aluminum as stabilizer. This alloy, based on Nickel or Zinc doping, gives a much higher yield strength to the stabilizer without compromising too much its electrical performances at low temperature (typical values are $\sigma_{\text{yield}}=85$ MPa and $\text{RRR} > 400$).⁴ The resulting winding pack is very compact radially and it could be fitted between the tracker and the electromagnetic calorimeter. The other choice, for the very large aperture and high field solenoid of the CMS magnet, was to reinforce the high pure aluminum stabilizer with an aluminum alloy showing the best mechanical performances at cold temperature. In this design, a double extruded profile of AA6082, welded to the aluminum stabilized via two electron beam guns, gives the required resistance to the conductor, limiting the overall strain to about 0.15%. This design assures the highest stability, due to the optimal RRR of the high purity aluminum, combined with the outstanding mechanical properties of the AA6082 alloy. However the inner high purity aluminum is fully in the plastic domain once the magnet is powered, consequently the electrical performances of the conductor will slightly degrade with the increasing number of powering cycles (conductor aging) (Fig. 11).

6.4. Winding techniques

From the previous sections, it is clear that the superconducting conductor is actually a compound and complex masterpiece of engineering, whose part carrying the current is only one element (although still the most important one). This is by the way the most evident difference between a cable for accelerator magnets and a conductor for large HEP detector magnets. An accelerator magnet

requires a high current density and therefore a compact winding, from which the magnetic stored energy can be quickly extracted, a superconducting conductor for detector magnet on the contrary has to be well stabilized and fully protected against quenches, as the energy extraction is made difficult by its high inductance.

It is also clear that the winding techniques cannot be the same as for an accelerator magnet. The conductor is much stiffer and its length could reach 50 km, as in the case of the CMS magnet, where for practical reasons, it has been decided to put in series 20 lengths of 2.5 km each. A dedicated winding machine has to be built specifically for each detector magnet, in order to bend the conductor in turns of the required radius and then compact them to have a monolithic winding pack. No relative movements of the turns are allowed when energized, because a quench could be generated by the smallest release of energy within the coil.

The following operations have to be performed during cabling winding:

- (1) De-spooling, as the conductor usually comes spooled onto large drums.
- (2) Cleaning, to assure a proper surface for the conductor insulation.
- (3) Bending at the calculated radius. During this process the cross-section of the conductor is deformed (key-stoning) and an accurate evaluation of this effect has to be made to avoid sliding out of tolerance just by piling up turns.
- (4) Insulating with a glass-fiber tape.
- (5) Packing of the turns and monitoring of the geometrical tolerance.

Then the winding pack is ready to be impregnated, preferably under vacuum, as it will be described in the Section 6.5.

The winding operation has to be carried in a controlled area, where temperature and humidity are kept constant and dust limited to a minimum. Depending on the complexity of the coil design, other operation are required, such as conductor leads preparation for jointing, installation of temperature, voltage, strain gauges, etc.

6.5. Vacuum impregnation

Woven fiberglass tapes can be found on the market already impregnated with thermo-setting epoxy resin. The conductor is then wrapped with the impregnated fiberglass tape during winding. A final layer of this tape is wrapped around the wound coil as ground insulation. The wrapped coil is installed in an oven and cured using the appropriate thermal cycle indicated by the prepreg tape supplier. This method is cheap to follow but it has some inconvenient. The encapsulation is porous, so that dirt and moisture can contaminate the coil and can potentially cause turn-to-turn shorts.

Impregnation under vacuum is on the contrary the best practice. It is rather expensive because it requires the fabrication and assembly of a dedicated vacuum oven, with its associated tooling to manipulate the complete winding pack. A vacuum impregnation system comprises:

- (1) The epoxy de-aerating tank, fitted with mixing vanes connected to a mixing motor and a heater, so that the resin can be mixed and de-aerated at warm temperature.
- (2) The potting tank or vacuum oven, with fittings to inject the resin and evacuate air. The resin injection can take several hours while the curing can last even days, depending on the size of the winding pack.

This process is particularly critical at this stage of manufacturing as a failure in the resin impregnation could eventually lead to reject the whole coil, thus the know-how of an

⁴ Atlas Central Solenoid Technical Design Report, April 1997, page 25

experienced company in vacuum impregnation is of paramount importance.

7. Cryogenics, vacuum and other ancillary systems

7.1. Cryogenics design

The superconducting technology is strictly linked to the development of cryogenics plants that are necessary to supply the liquid helium to keep the superconducting cable at the required temperature. We have seen in the previous section, that the current carrying capacity of the cable is a function of its temperature. Practically, most of the superconducting magnets for HEP detectors use liquid helium at 4.5 K and 1 ata. For special high field magnet, supercritical helium at 1.9 K has been used, but the complexity of pumping over the helium bath to lower its saturation temperature makes this solution quite expensive.

The process for producing liquid helium is known since Kamerlingh Onnes in 1908. Modern cryogenics plants supply nowadays 1 kW of cooling power at 4.5 K, equivalent to some hundreds grams per second of liquid helium,⁵ that is largely enough to cool a HEP detector magnet, taking into account the static and dynamic loads of the system (Fig. 12).

Typical cryogenics loads for a large superconducting solenoid are listed in Table 2

In Fig. 13 a simplified layout of the cryogenics and vacuum services is represented. On surface, large vessels contain gas He ready to be injected into the warm compressors that compress the gas to about 20 bars at 300 K. The gas is then sent to the high pressure inlet of the He liquifier, also called “cold-box”, that is usually located in a service area not very far from the detector itself. In the cold-box helium gas passes through a series of heat-exchangers and expansion turbines, each time reducing its pressure and temperature. At the final expansion, the gas helium liquifies, at a temperature of 4.5 K at 1 ata. The liquid He is transferred to a storage dewar very close to the detector magnet, via a vacuum insulated transfer line. The helium enters then the magnet vacuum enclosure, via a valve-box, to cool the superconducting winding pack. The return line carries the saturated vapor He coming out of the magnet back to the cold-box, where it passes through the heat-exchangers to get back to the compressors. The whole cycle is fully instrumented and controlled by PLC, reducing human interventions to solve faulty states or exceptional transient cases.

The circulation of the liquid helium inside the magnet could be done either via a forced flow or by density gradient. The first method can be applied to all magnet geometries and allows a precise tuning of the flow inside the winding pack. It requires, however, cryogenics pumps that are rather delicate and expensive, moreover a fraction of the cooling power is lost in the pump itself. The thermosiphon method can be applied only when the design of the winding pack allows for natural circulation of the liquid helium, driven by a density gradient due to the increasing vapor title in the fluid. This method being fully passive, it is the preferred one for most of the latest HEP detector solenoids. The driving force depends on the height of the liquid helium bath free surface with respect to the lowest point in the winding pack cooling loop, times the difference in density of the fluid in these two locations.

7.2. Vacuum insulation

The cold-box, the liquid–helium transfer lines, the valve-box, the dewar and the magnet vacuum enclosure are kept under

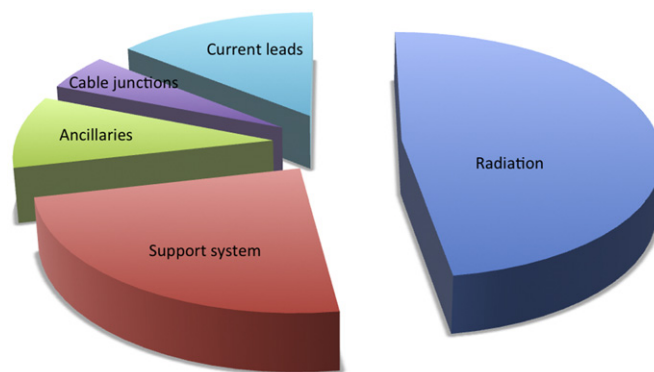


Fig. 12. Typical distribution of cryogenics losses.

Table 2

Typical thermal loads for large superconducting magnets.

Static thermal loads at 4.5 K (W)		Dynamic thermal loads at 4.5 K	
Radiation	100	Eddy currents on ramping	60 W
Support system	50	Eddy currents on slow-discharge	200 W
Ancillaries	20		
Cable junctions	10		
Static thermal loads at 70 K			
Thermal screens	3000	Current leads He flow (20 kA)	2.5 g/s

vacuum to limit the thermal losses. Thus the vacuum pumping system has to be reliable and robust to allow continuous operation of the cryogenics system. It consists usually of a fore vacuum unit that assures a rough vacuum of some mbar at the exhaust of one or more high vacuum pumps, located directly on the magnet vacuum enclosure. To be noted that, due to the magnetic stray field emerging from the detector magnet, only stationary HV pumps can be operated, usually oil-diffusion pumps. The procedure for vacuum pumping starts with the fore vacuum pumping unit that lowers the pressure inside the magnet cryostat to about 10^{-3} mbar to allow the switching on of the high vacuum pump. The latter has to lower the pressure to better than 10^{-5} mbar in order to start the circulation of cold helium gas in the winding pack. To limit the mechanical stress caused by high temperature gradients into the magnet, the maximum difference in temperature of any point shall be kept lower than 30–40 K. Once the temperature in the magnet cryostat is lower than 77 K, most of the residual air condensates over the cold surfaces and the overall pressure falls quite rapidly. Finally, when the magnet reaches its nominal temperature of 4 K, then the cryogenic pumping of the cold surfaces is large enough to keep the vacuum level well below 10^{-6} mbar and the HV pump can be switched off. The most critical period in the whole sequence, that depending on the cold mass size could take over 3 weeks, is when the magnet temperature is between 150 and 20 K. In this range, the active pumping has to guarantee a good insulation vacuum to avoid condensation of air humidity onto the external magnet vessel that could cause severe damages to the detector.

7.3. Thermal shields

We have said that, in order to limit the thermal losses, all the components working at cryogenic temperature are enclosed into a vacuum vessel. The insulation vacuum there protects against losses by air-convection, but also radiation, from the warm inner surfaces of the vessel into the cold mass, has to be stopped. This is done by interposing a thermal shield, cooled at a temperature

⁵ 1 kg of liquid helium at 4.5 K and 1 ata has a volume of about 8 l.

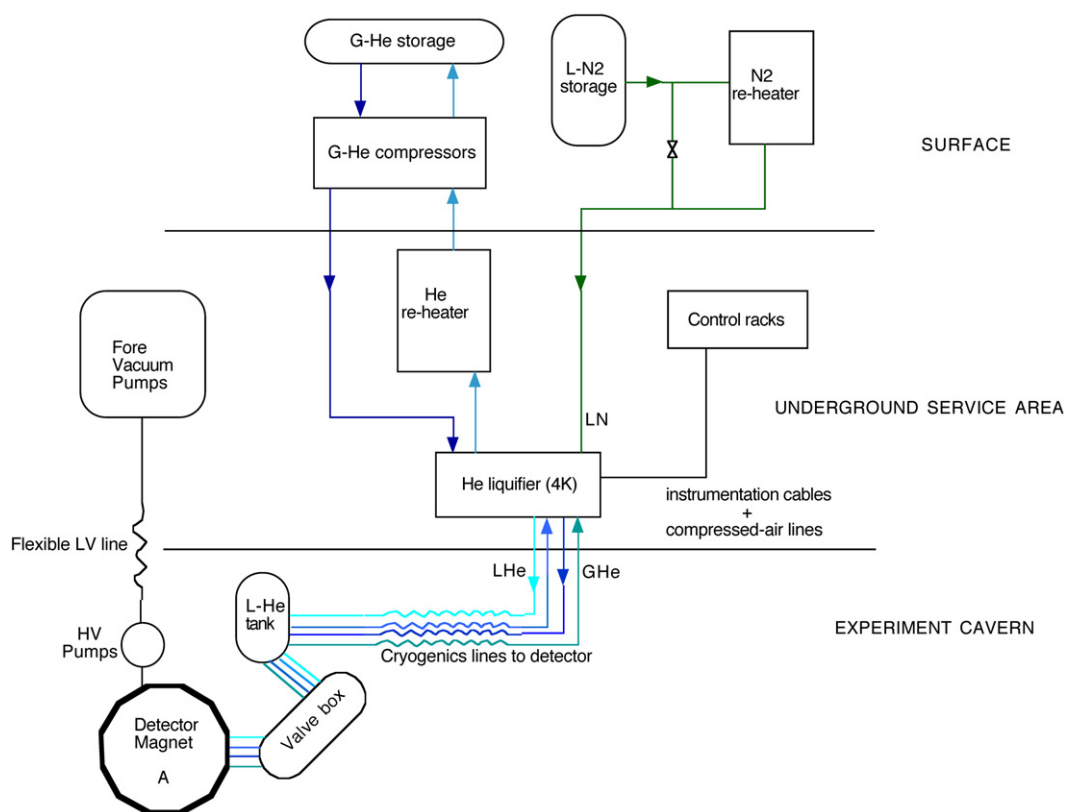


Fig. 13. Simplified schematics of cryogenics and vacuum services.

between 40 and 80 K that intercepts most of the radiation coming out from the vessel. The thermal shield is very effective, but it complicates the design of the cold mass and the associated piping. It usually consists of a metallic sheet cooled by a flow of pressurized helium gas and carrying a multilayer insulator blanket. The thermal shield is supported by low-conductivity posts designed to let the different component slide under the different movements induced by thermal gradients.

Generally speaking the design of the cryogenics and vacuum systems is critical as the operation of any superconducting magnet depends on the reliability of these systems and their associated services. Pumping and cooling down times are given by design parameters that, once decided, cannot be easily modified when the system has been built. Adequate redundancy has to be foreseen where necessary and it is also important to have predictive maintenance in order to limit the downtime when the experiment is taking data.

8. Power circuit

The main role of the powering circuit is to provide precise current value and protect the magnet against faulty states. The great majority of HEP detector magnets are powered with DC constant current, but there are a few examples of magnets powered with a DC pulsed current.⁶ The main circuit components are the power supply unit, the main breakers, the protection resistors and diodes and of course the detector magnet. The power supply unit provides the DC current to the magnet. Depending on the current value and the requirements on current

ripple and precision it can be done in different technology. It is out of the scope of this chapter to describe this in details. We can just add that one of the most important problems to solve is the read-out of the actual current level. For values above 10 kA is largely diffused the use of DCCT devices (Direct Current Current Transformers) also known as zero-flux current transformers. They allow for a precise measurement of the DC feeding with a resolution of some ppm.

The power supply unit is dimensioned in function of the current ramping rate (di/dt) and the resistive (R) and inductive (L) charge of the circuit. The output voltage must satisfy the relationship:

$$V = iR + L \frac{di}{dt}$$

In steady-state the output voltage is given only by the resistive load of the coil (if not superconducting), plus the voltage drop across the current-leads and the lines connecting the power supply to the magnet. For a resistive magnet the output voltage can be of the order of 500 V, whilst for superconducting magnets it is normally limited to 5–10 V (Fig. 14).

Current-leads for superconducting magnets are probably the most difficult piece of engineering of the power circuit. As they represent at one time the transition piece from resistive to superconducting cable and from room temperature to liquid helium one, their design involves almost all the disciplines. Detailed design of high current leads can be found on almost all HEP detectors technical proposals. Here we give only a brief description, focusing on superconducting magnets. Current density in the resistive part of the current lead is limited to 10–15 A/mm², whilst once in the superconducting part, it rises to about 1 kA/mm² or more. As the superconducting part is normally cooled by liquid helium, the same fluid is evaporated along the resistive part to keep cooled the bulk resistive conductor. Thus

⁶ For example, the Chorus hexagonal magnet at CERN was pulsed with a 3200 A current for 12 ms, one pulse every 7 s.

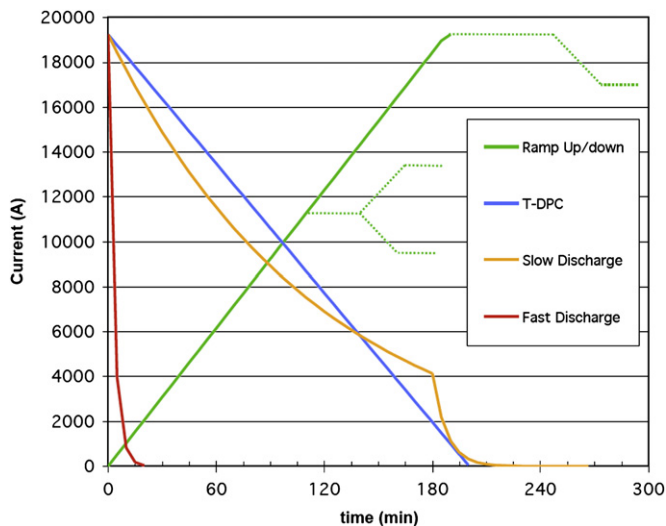


Fig. 14. Typical current ramping curves for a superconducting magnet: the green and blue ones indicate current ramp via the power supply, the red and yellow ones indicate current ramping down via the dump resistor. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the design foresees a massive resistive (made of copper or aluminum) conductor, usually consisting of a braid of multiple interlaced strands, through which the cold helium gas flows and that is then soldered or crimped to a massive foot, to which the superconducting cable is soldered. The whole assembly is contained inside a pressure cylinder that is, on its turn, located inside a vacuum vessel. One of the problem is to guarantee the right helium flow through the system: at the bottom of the current lead there must be enough helium to keep the superconducting cable at the right temperature and, at the current lead head, the temperature of the escaping gas helium has to be above the local dew point to avoid any condensation. This is obtained with a set of electric heaters that supply the heat necessary to warm up the helium gas, in addition to the joule effect present in the resistive part of the current lead. A PID controller acts on the liquid helium supply and on the heaters, to balance the contribution of the joule effect that is dependent on the current level.

9. Magnet protection issues and safety aspects

9.1. Instrumentation, controls and safety systems

Instrumentation and controls play a fundamental role to assure the reliable and safe operation of modern HEP detector magnets. The number of parameters to be monitored ranges from a few tens for resistive magnets to many hundreds for large superconducting ones. Typical variables include current value, voltage, temperature, cryogen and water flow and pressure, forces and displacements, field values, status of contactors and breakers, etc. The monitoring and control system is based on programmable logic controllers that survey all the process parameters, both for normal operation and for faulty states, that are not dangerous neither for the equipment nor for the personnel. Severe faulty states (such as quenches, electrical shorts, etc.) are handled by a fully hardwired safety system that takes over the standard control processing anytime its own dedicated transducers spot a risky situation. The safety system has usually much less channels than the central one, but all the sensors and actuators are fully cabled, in order to avoid any network delay. Moreover the alarm-action matrix, that sets the actions to be

taken as a function of the alarms present, can only be modified by experts when the magnet is down. The magnet safety system is also connected with the detector safety controller, in order to actuate all the interlocks necessary to protect the detector from an emergency state of the magnet (a typical example is during a current ramping up or down, when the detector high voltage channel are usually switched off). On the other way, the detector safety controller allows the magnet to be ramped up only when the detector configuration is the right one, i.e. the yoke is fully close, the safety warnings are switched on, etc.

During normal operation, the set-value of magnet current can be changed within the limits and at the rate given by the control system. Ramping from zero to full current can take from a few minutes to several hours, depending on the magnet nominal current, coil inductance and the power supply output voltage. Ramping down can be done either via the power supply, usually at the same rate as ramping up, or via a fully passive resistor bank that can be set to two or more different configurations, slow dump, fast dump or any intermediate.

9.2. Dump resistors

We have seen in Section 8 that the powering circuit can be considered as a RL circuit, the resistive part being given, in normal operation, by the coil winding (in case of resistive magnets) and the powering lines connecting the current supply to the coil. The magnetic energy stored in the magnet has to be quickly extracted out of the winding each time a faulty state of the magnet or the detector requires a fast dump. This is commonly done by connecting in parallel with the coil winding a resistor bank, whose resistance can be set to at least two different values (R_{slow} and R_{fast}), giving two different discharge time constants:

$$\tau_{\text{slow}} = L/R_{\text{slow}}(\text{s}^{-1}) \quad \text{and} \quad \tau_{\text{fast}} = L/R_{\text{fast}}(\text{s}^{-1})$$

The current discharge is described by the differential equation:

$$L \frac{di}{dt} = R(t)i(t)$$

where R represents the sum of the resistance of the coil plus the external circuit, including the discharge-bars and the resistor banks. It is important to notice that R changes with time due to the joule effect. The effect of self-inductance of the external mandrel of the coil and the mutual inductance between the mandrel and the coil itself is here neglected. The above equation sets as well the maximum voltage and current rate during a discharge. For safety reasons, the maximum allowed voltage during a fast dump is of the order of 1 kV. Higher values would require complicated turn-to-turn and coil-to-ground insulation techniques.

In superconductive magnets dump resistors are of paramount importance, because they have to extract as much stored energy as possible in the shortest time, in order to protect the cable from burning. In this case, the resistors are permanently connected to the winding, also during normal operation. The voltage drop at their leads is limited by the fact that they are shunted by the superconducting coil, whose resistance is zero. Only when a quench occurs and the coil transits to a resistive state, a large fraction of the current takes the way of the dump resistor.

In large HEP detectors, dump resistors have to take away up to 1 GJ of stored energy. This implies oversized bus-bars connecting the coil to the resistors and large banks that measure hundreds of cubic meters. Compact dump resistors banks are developed when there are space concerns or in case the cavern ventilation cannot take the thermal load. These are water filled vessels that contain the resistors, the energy dumped by joule effect is taken by the water enthalpy. Special care has to be taken designing such a

system in order to avoid the critical heat flux that could burn-out the resistors, by creating a thermal resistive vapor barrier between the resistors and the bulk water. The production of hydrogen gas by water hydrolysis has also to be taken care of.

9.3. Stray field

The stray field present outside the detector imposes precautions both for what concerns the choice of equipment supposed to run in proximity of the detector magnet and for the operations that are allowed when the magnet is switched on. It is clear that electrical driven motors are largely affected by the stray field and they are usually replaced by air-driven motors or shielded with massive iron screens. Same care has to be put on electro-actuated valves and instrumentation in general. A test to check the behavior of any component supposed to work in presence of a magnetic stray field is highly recommended. As a general rule, any work in presence of a stray field exceeding 10 mT shall be avoided, specially if it involves the displacement of heavy metallic pieces via a crane or any similar lifting device.

9.4. Helium release

The release of large quantities of helium gas into the experiment cavern can occur either during a magnet quench or in case of accident, for instance when a vacuum insulated liquid helium line gets damaged. In both cases a large fraction of the liquid helium contained into the magnet cooling circuit, evaporates and expands, escaping to atmosphere through release valves or burst disks. It is important to evaluate the maximum quantity of helium that could be released in the worst possible scenario. It is worth recalling that 1 l of liquid helium expands to some 750 l of gas at room temperature. Considering that the amount of liquid helium contained into a large HEP superconducting magnet can reach one cubic meter, this corresponds to some 750 m³ of gas helium at room temperature. The cavern size and ventilation shall be adapted to this, knowing also that, in order to avoid any risk of asphyxia, the oxygen content shall be maintained above 12–15%. Oxygen deficiency hazard sensors trigger the evacuation alarm whenever a dangerous threshold is reached.

10. Field mapping

We have said in the Section 1, that the deflection of the charged particle depends on three parameters: the strength of the field, the length of the trajectory in the field and the momentum of the particle. The size and strength of the field have to be measured, so that by measuring the deflection of the particle trajectory, physicists can find its momentum. Depending on the geometry, the measurement of the *B*-field inside the detector, can be not trivial at all.

Finite elements codes help in modeling the magnetic field in the detector region of interest. The precision of these models can reach a few percent, providing that the material properties for the iron yokes are well known and the boundary conditions are properly written. By using these models, a full measurement of the *B*-field is not mandatory anymore. An adequate array of probes in significant locations can be used to calibrate the model and consequently know the *B*-field vector in any volume covered by the model itself. However, specially in the detector tracking region, a precise field map is often performed by a scanning machine that holds several probes and maps the volume by moving instrumented arms along a pre-defined path.

The field value in air is commonly measured by NMR probes or Hall-effect sensors. The first give an absolute value but they need

to be placed in a homogeneous zone, they are quite bulky and expensive, specially in terms of read-out, the latter are compact and easy to operate, but they require an accurate calibration around the nominal value of the field they have to measure. It is sometimes important to measure the magnetic induction inside the iron yoke. This can be done by using flux-loops, i.e. windings around a massive steel block. The variation of the field inside the block generates a voltage change in the loop that can be measured and integrated in time. This method is normally used only during a fast dump to maximize the signal-to-noise ratio.

11. Applications of HEP detector magnet technology outside particle physics

Modern superconducting magnets for HEP detectors have benefitted of a 50 years continuous R&D program that involves different technologies. Powerful superconducting electromagnets are used in magnetic levitation (maglev) trains, Magnetic Resonance Imaging (MRI) and Nuclear Magnetic Resonance (NMR) machines, magnetic confinement fusion reactors (e.g. tokamaks) etc. The most common use of superconducting magnets is for MRI scanners. Magnetic Resonance Imaging, a recent application of Nuclear Magnetic Resonance (NMR), is primarily a medical imaging technique most commonly used in radiology to visualize detailed internal structure and limited function of the body. MRI provides much greater contrast between the different soft tissues of the body than computed tomography (CT) does, making it especially useful in neurological (brain), musculo-skeletal, cardiovascular, and oncological (cancer) imaging. Unlike CT, it uses no ionizing radiation, but uses a powerful magnetic field to align the nuclear magnetization of hydrogen atoms in water body-tissues. Radio frequency (RF) fields are used to systematically alter the alignment of this magnetization, causing the hydrogen nuclei to produce a rotating magnetic field detectable by the scanner. This signal can be manipulated by additional magnetic fields to build up enough information to construct a detailed image of the body. An interesting feature of these magnets is the way they are powered. Once the magnet has been energized via an external power supply, the magnet winding is short-circuited with a piece of superconductor. The winding becomes a closed superconducting loop, the external power supply can be turned off, and persistent currents will flow for months, preserving the magnetic field. The advantage of this persistent mode is that stability of the magnetic field is better than what is achievable with the best power supplies, and no energy is needed to power the windings. The short circuit is made by a 'persistent switch', a piece of superconductor inside the magnet connected across the winding ends, attached to a small heater. In normal mode, the switch wire is heated above its transition temperature, so it is resistive. Since the winding itself has no resistance, no current flows through the switch wire. To go to persistent mode, the current is adjusted until the desired magnetic field is obtained, then the heater is turned off. The persistent switch cools to its superconducting temperature, short circuiting the windings. The current and the magnetic field will not actually persist forever, but will decay slowly according to a normal *L/R* time constant:

$$I = I_0 e^{-(R/L)t}$$

where *R* is a small residual resistance in the superconducting windings due to joints or a phenomenon called flux motion resistance. Nearly all commercial superconducting magnets for MRI scanners are equipped with persistent switches.

Magnetic confinement superconducting magnets are commonly used in experimental nuclear fusion reactors to confine the plasma and avoid any contact with the reactor vessel inner

wall. The main difference between these kind of magnets and HEP ones is the fact that they are often operated in a semi-DC state, i.e. they are ramped up and down about every seconds and this makes their design much more complex than a DC-operated magnet. Anyhow the basis of the development of nuclear fusion reactor magnets come undoubtedly from the long work done and the tens of magnets constructed and operated in the HEP laboratories worldwide.

Acknowledgements

The author wishes to acknowledge the great help given by Alain Hervé, from CERN, in discussing arguments on the design of magnets for HEP detectors and Pasquale Fabbriatore, from INFN Genova, in reading the whole article before publication.

Further reading

- [1] M. Wilson, Superconducting Magnets, Oxford Sciences Pub., 1987.
- [2] G. Petrucci, Théorie et pratique des aimants, CERN Enseignement Technique, 1994.

- [3] CMS Collaboration, The Magnet Project, Technical Design Report, CERN, 1997.
- [4] Atlas Collaboration, EndCap Toroids, Technical Design Report, CERN, 1997.
- [5] Atlas Collaboration, Central Solenoid, Technical Design Report, CERN, 1997.
- [6] A. Hervé, IEEE Trans. Appl. Supercond. 10 (1) (2000) 389.
- [7] M. Thomas, Taylor, Detector Magnet Design, CERN Accelerator School, 2002.
- [8] F. Herlach, N. Miura, High Magnetic Fields, World Scientific, 2003.
- [9] A. Yamamoto, IEEE Trans. Appl. Supercond. 14 (2) (2004) 478.
- [10] A. Gaddi, The CMS Magnet: Main Technological Breakthroughs, Astroparticle, Particle and Space Physics, Detectors and Medical Physics Applications, World Scientific, 2004, pp. 260–264.
- [11] Jack T. Tanabe, Iron Dominated Electromagnets, World Scientific, 2005.
- [12] P. Fabbriatore, Design principles of thin high field superconducting solenoids, Technological challenges for LHC detectors, CERN, , 2005.
- [13] P. Fabbriatore, Large superconducting solenoids in HEP experiments: 40 years of developments, EUCAS 8th Conference, 2007.
- [14] A. Gaddi, Considerations about an Improved Superconducting Cable for Linear Collider Detectors, Detector Note CLIC-PH-2009-001, May 2009.
- [15] A. Ballarino, J. Cryogenic Soc. Jpn (2009).
- [16] A. Gaddi, F. Ramos, Design of a Compact Dump Resistor System for LCD Magnet, Detector Note CLIC-PH-2010-003, March 2010.
- [17] B. Curé, CMS Magnet Operation Manual, CERN/EDMS doc. Nr. 1049723, March 2010.
- [18] A. Hervé, Mod. Phys. Lett. A 25 (20) (2010) 1647.